Deeply Virtual Compton Scattering off ^{4}He:

New results and future perspectives

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(On behalf of the CLAS collaboration)

NPWG - CLAS Collaboration Meeting (March 28-31, 2017)

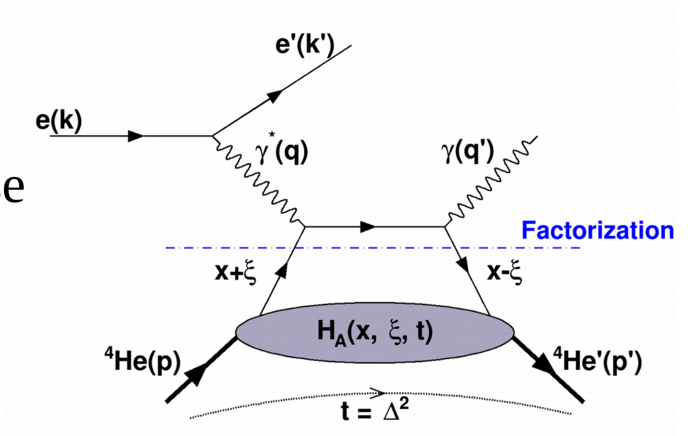
DVCS off nuclei

Two DVCS channels are accessible with nuclear targets:

◊ **Coherent DVCS: $e^- A \rightarrow e^- A \gamma$**

→ Study the partonic structure of the nucleus.

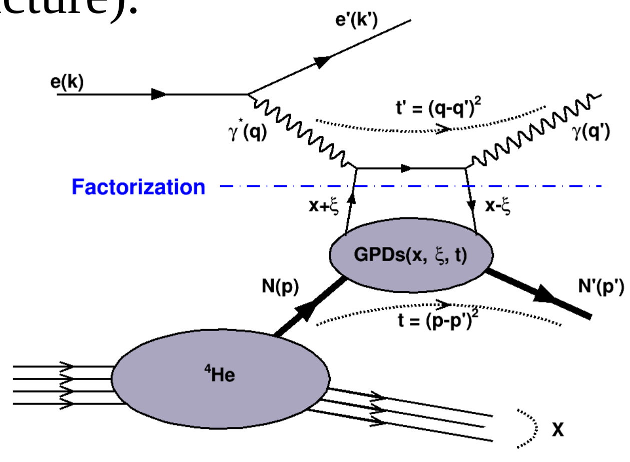
→ One chiral-even GPD (**$H_A(x,\xi,t)$**) is needed to parametrize the structure of the spinless nuclei (^{4}He, ^{12}C, ^{16}O, ...).



◊ **Incoherent DVCS: $e^- A \rightarrow e^- N \gamma$**

→ The nucleus breaks and the DVCS takes place on a nucleon.

→ Study the partonic structure of the bound nucleons (4 chiral-even GPDs are needed to parametrize their structure).



conserve nucleon spin

unpolarized	**$H(x,\xi,t)$**	**$\tilde{H}(x,\xi,t)$**	**polarized**
	$E(x,\xi,t)$	**$\tilde{E}(x,\xi,t)$**	

flip nucleon spin

Nuclear spin-zero DVCS observables

The GPD H_A parametrizes the structure of the spinless nuclei (^{4}He, ^{12}C …)

$$\mathcal{H}_A(\xi,t) = Re(\mathcal{H}_A(\xi,t)) - i\pi Im(\mathcal{H}_A(\xi,t))$$

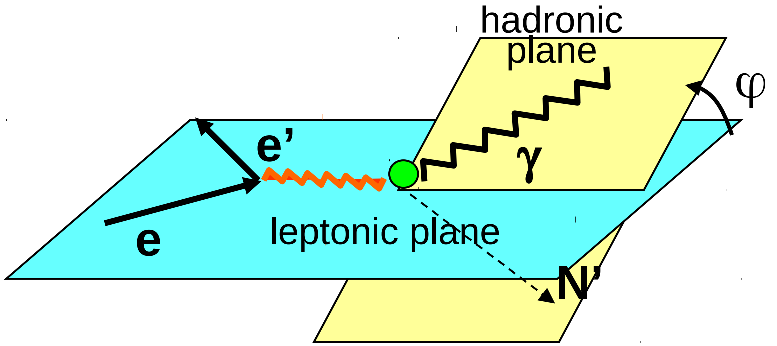
$$Im(\mathcal{H}_A(\xi,t)) = H_A(\xi,\xi,t) - H_A(-\xi,\xi,t)$$

$$Re(\mathcal{H}_A(\xi,t)) = \mathcal{P}\int_0^1 dx[H_A(x,\xi,t) - H_A(-x,\xi,t)]C^+(x,\xi)$$

Quark propagator

$$C^+(x,\xi) = \frac{1}{x-\xi} + \frac{1}{x+\xi}$$

→ Beam-spin asymmetry ($A_{LU}(\varphi)$) : (+/- beam helicity)



$$A_{LU}(\phi) = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

$$= \frac{x_A(1+\epsilon^2)^2}{y} s_1^{INT}\sin(\phi) \Big/ \Big[\sum_{n=0}^{n=2} c_n^{BH}\cos(n\phi) + \frac{x_A^2 t(1+\epsilon^2)^2}{Q^2}P_1(\phi)P_2(\phi)\, c_0^{DVCS} + \frac{x_A(1+\epsilon^2)^2}{y}\sum_{n=0}^{n=1} c_n^{INT}\cos(n\phi)\Big]$$

CLAS - E08-024 experimental Setup

$$e^- \, {}^4He \rightarrow e^- \, ({}^4He/pX) \, \gamma$$

6 GeV,
L. polarized

Beam polarization (P_B) = 83%

- **CLAS:**
  → Superconducting Torus magnet.
  → 6 independent sectors:
    → DCs track charged particles.
    → CCs separate e^-/π^-.
    → TOF Counters identify hadrons.
    → ECs detect γ, e^- and n [8°,45°].

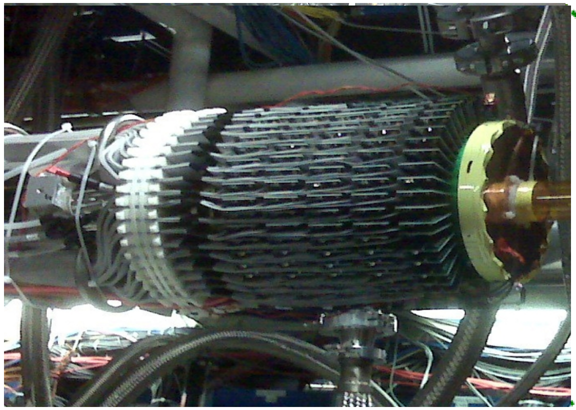
- **IC:** Improves γ detection acceptance [4°,14°].

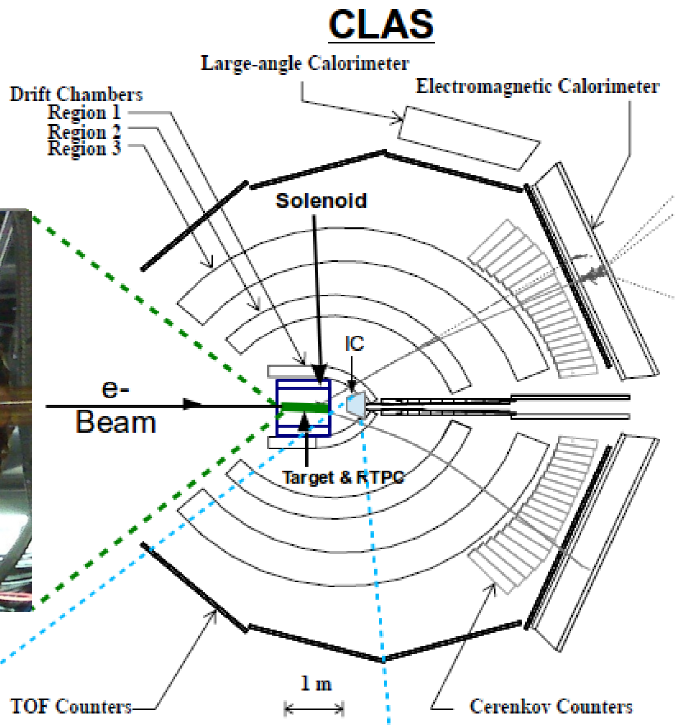
- **RTPC:** Detects low energy nuclear recoils.

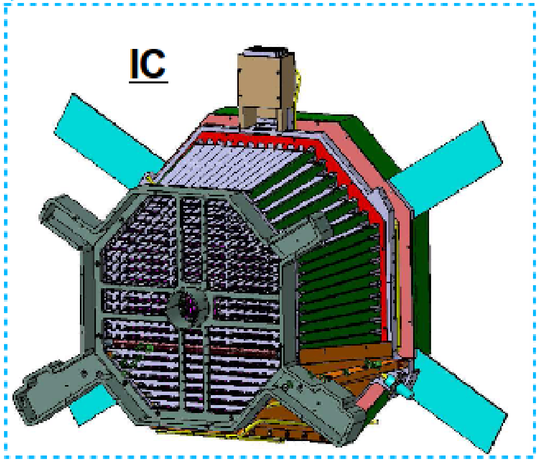
- **Solenoid:** - Shields the detectors from Møller electrons.
  - Enables tracking in the RTPC.

- **Target:** ^4He gas @ 6 atm, 293 K

RTPC







Coherent DVCS events selection

We select COHERENT events which have:

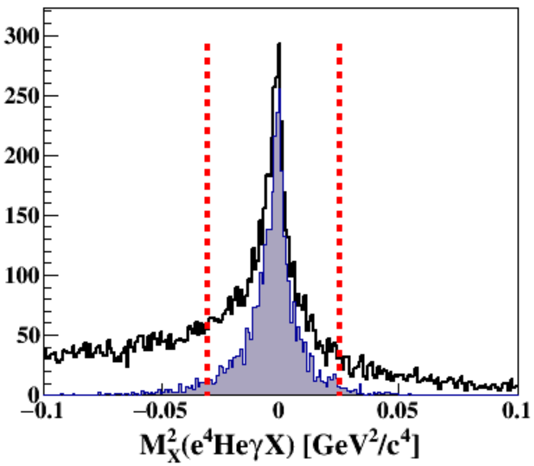
◊ Only one good electron, at least one photon and only one good ^{4}He.

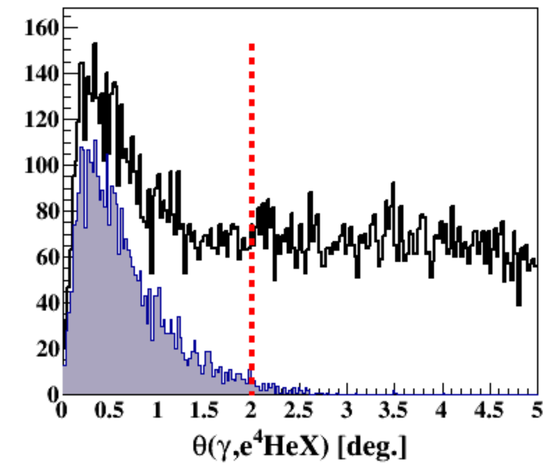
◊ $E\gamma > 2$ GeV and $Q^2 > 1$ GeV^2.

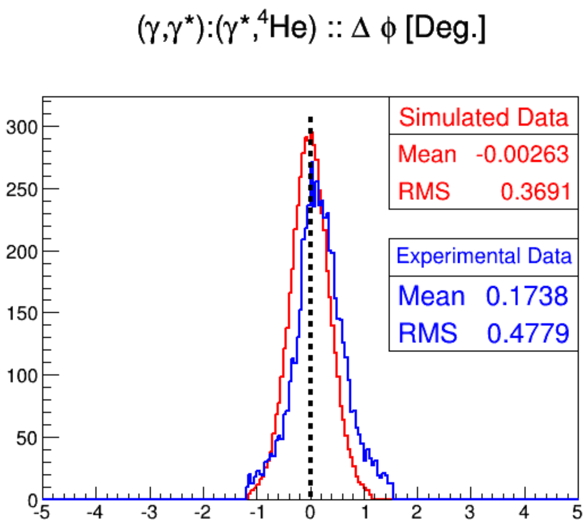
◊ Exclusivity cuts (3 sigmas).

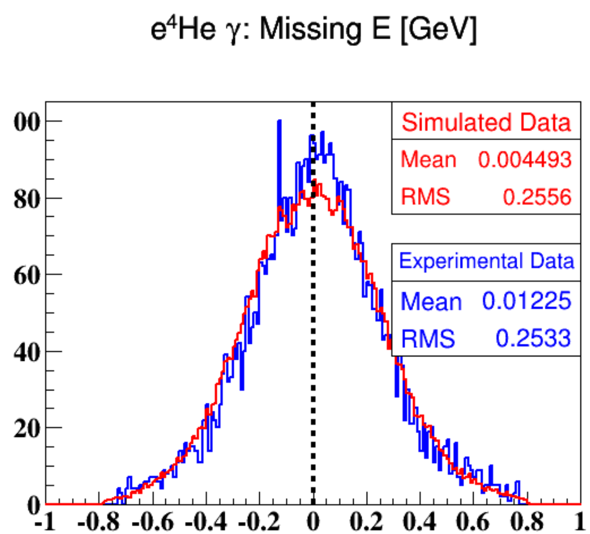
- In **BLACK**, coherent events before all exclusivity cuts.

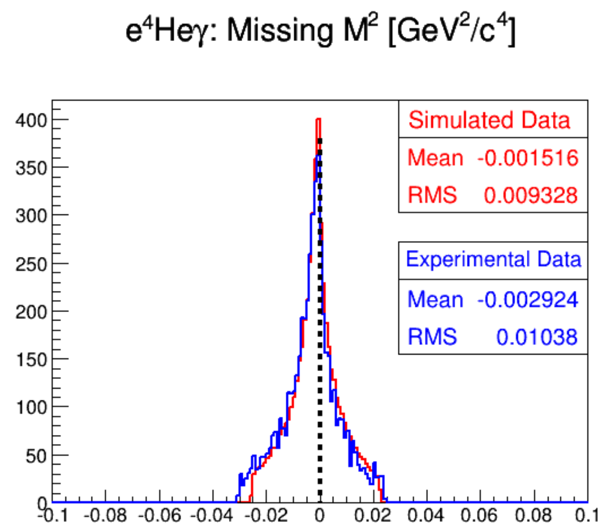
- In shaded, coherent DVCS events which pass all the other exclusivity cuts except the one on the quantity itself.





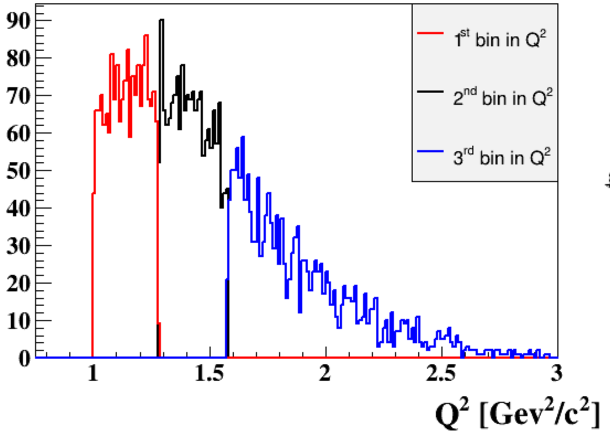


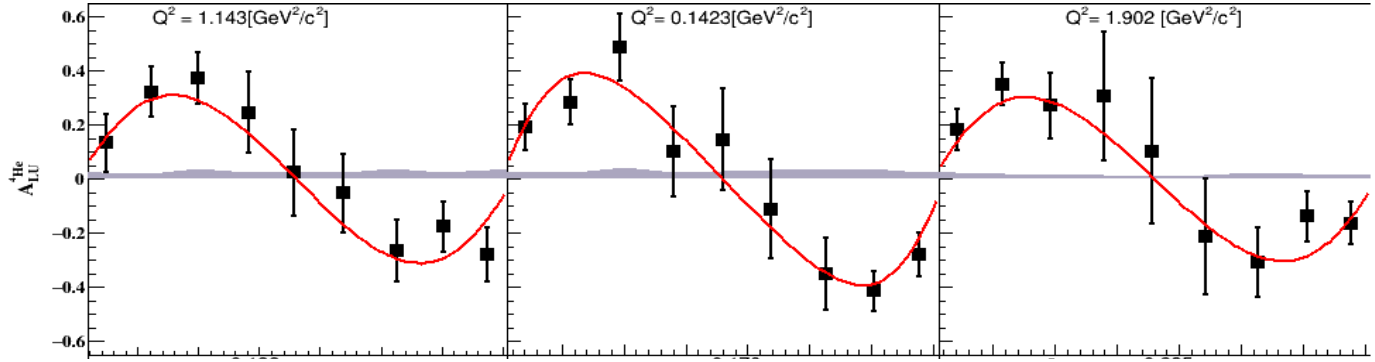


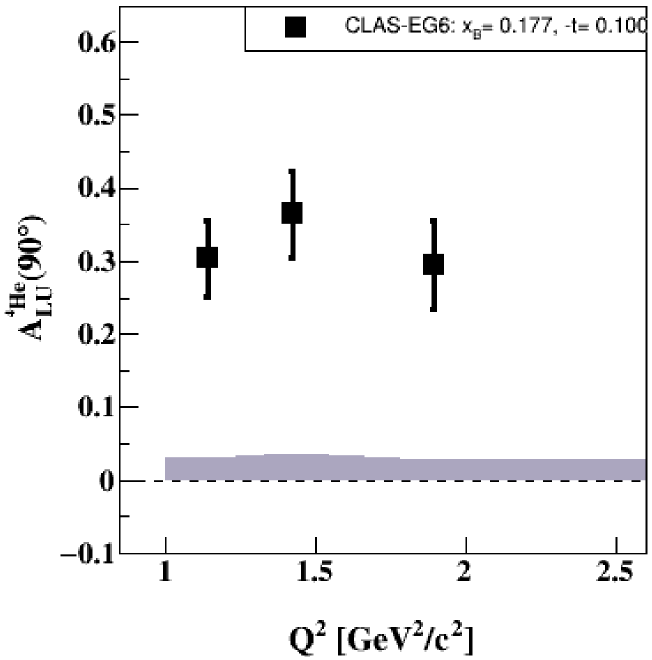


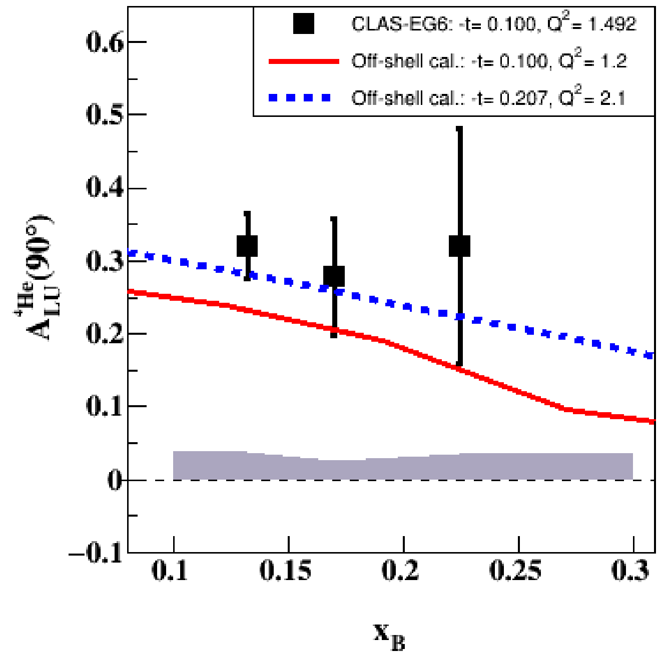
Coherent beam-spin asymmetries

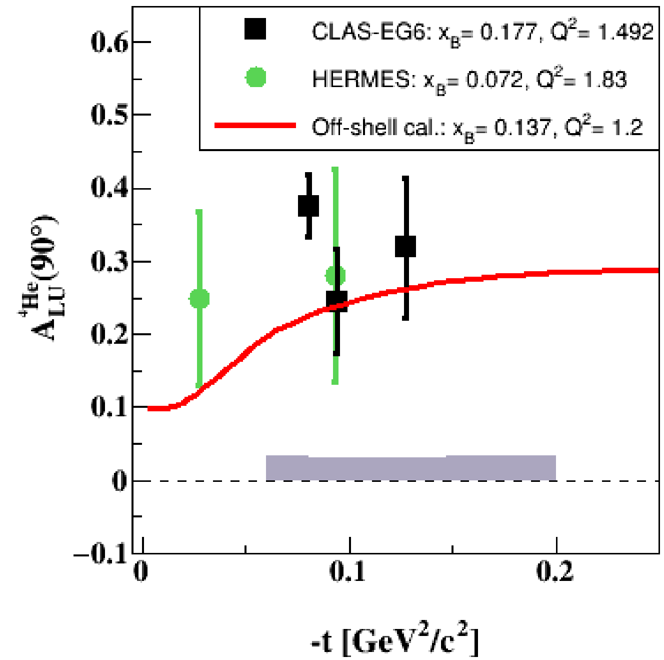
- Due to statistical constraints, we construct 2D bins -t or x_B or Q^2 versus φ











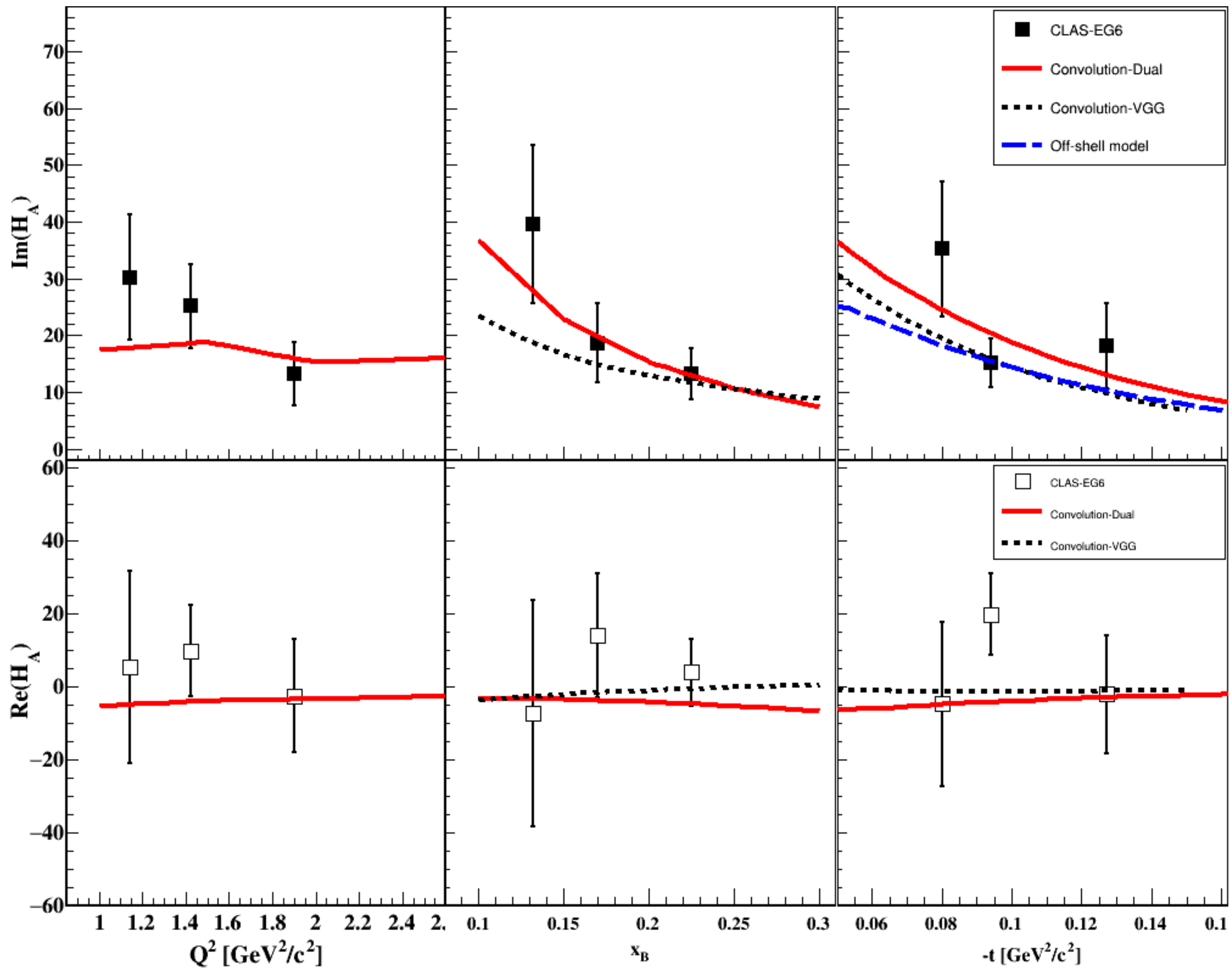
[1] Off-shell: S. Liuti and S. K. Taneja.Phys. Rev., C72:032201, 2005.
[2] A. Airapetian, et al., Phys Rev. C 81, 035202 (2010).

^{4}He CFF extraction

$$A_{LU}(\phi) = \frac{\alpha_0(\phi)\,\Im m(\mathcal{H}_A)}{\alpha_1(\phi) + \alpha_2(\phi)\,\Re e(\mathcal{H}_A) + \alpha_3(\phi)\left(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\right)}$$

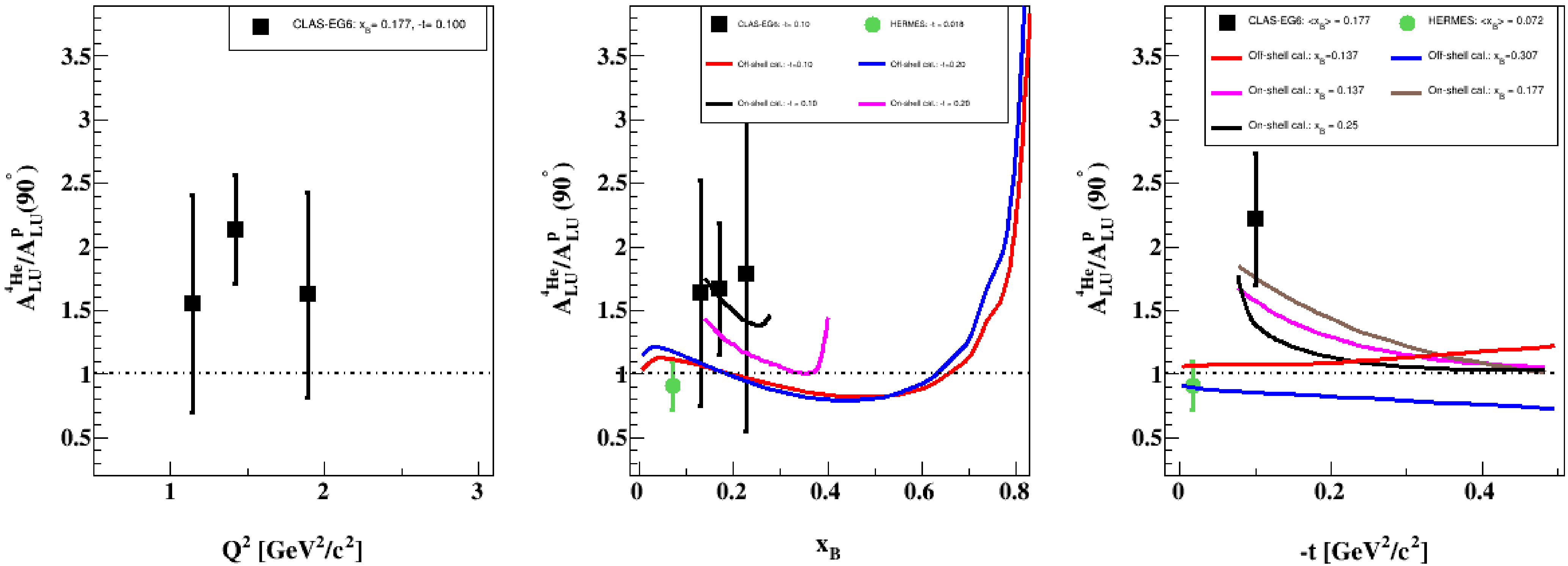
→ The first ever experimental extraction of the real and the imaginary parts of the He-4 CFF:

→ Difference between the precision of the extracted real and imaginary parts; A_{LU} is mostly sensitive to the imaginary part of the CFF HA.



Generalized EMC ratio

◊ Comparing the coherent asymmetries to the free proton ones:



→ Consistent with the enhancement predicted by the Impulse approximation model
[V. Guezy et al., PRC 78 (2008) 025211]

→ Does not match the inclusive measurement of HERMES.

→ Additional nuclear effects have to be taken into account in the nuclear spectral function calculations. [S. Liuti and K. Taneja. PRC 72 (2005) 032201]

Incoherent DVCS events selection

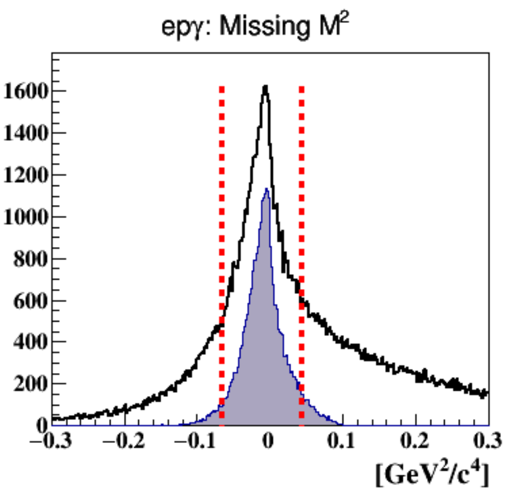
◊ Only one e⁻, at least 1γ and only one good p.

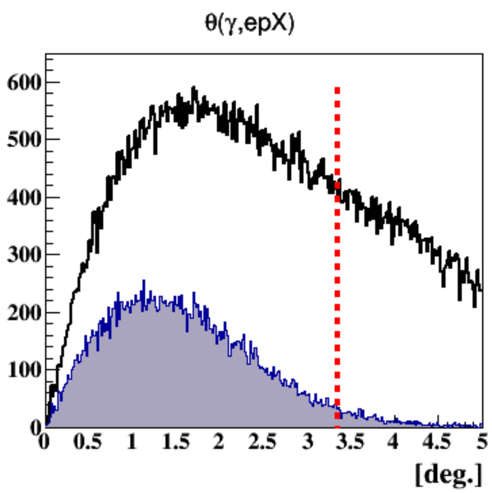
◊ Eγ > 2 GeV, W > 2 GeV/c^2 and Q^2 > 1 GeV^2.

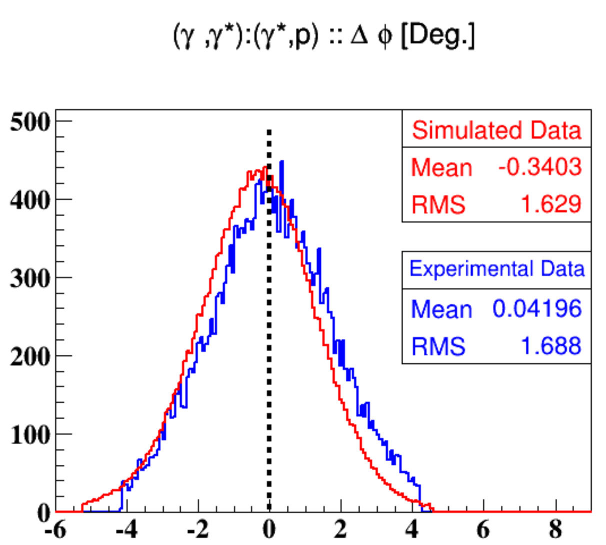
◊ Exclusivity cuts (3 sigmas).

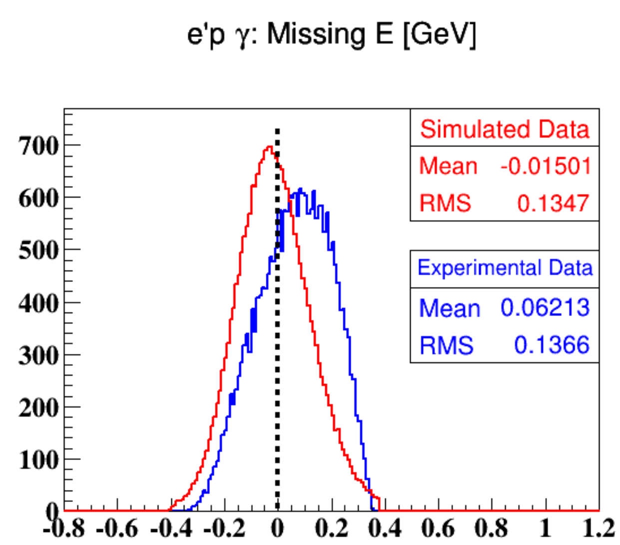
- In **BLACK**, coherent events before all exclusivity cuts.

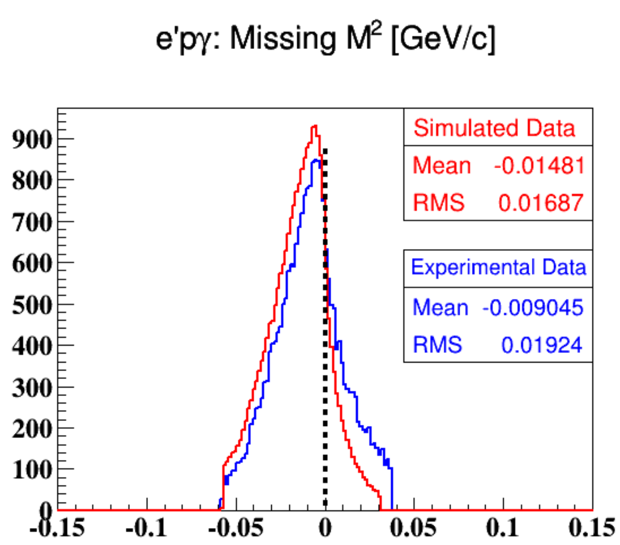
- In shaded, coherent DVCS events which pass all the other exclusivity cuts except the one on the quantity itself.







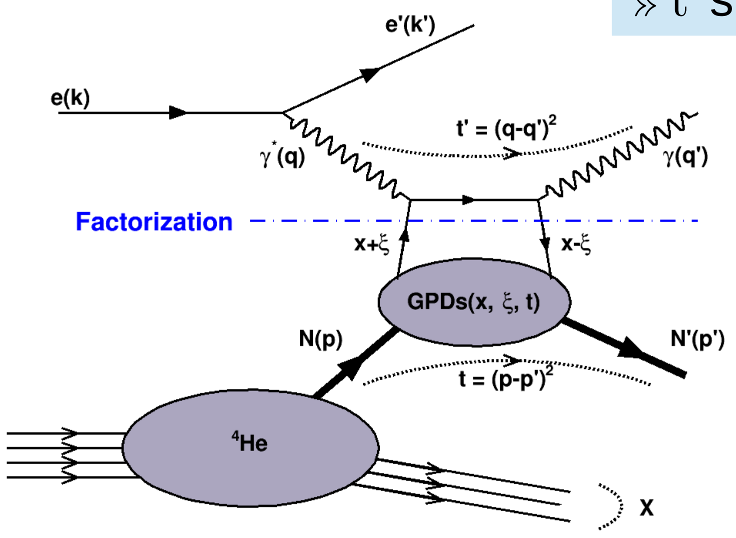


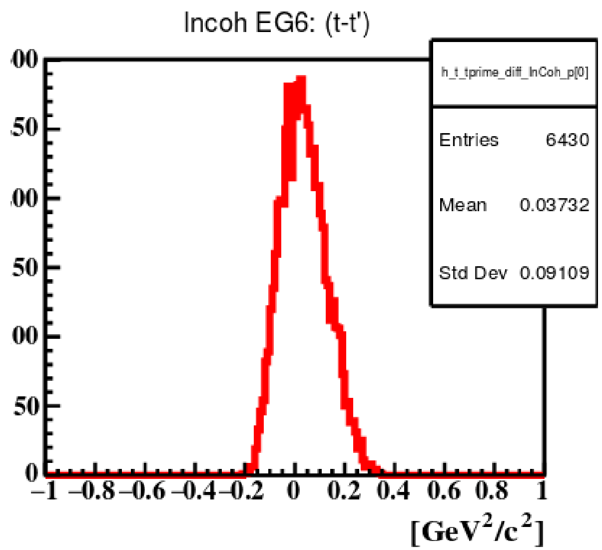


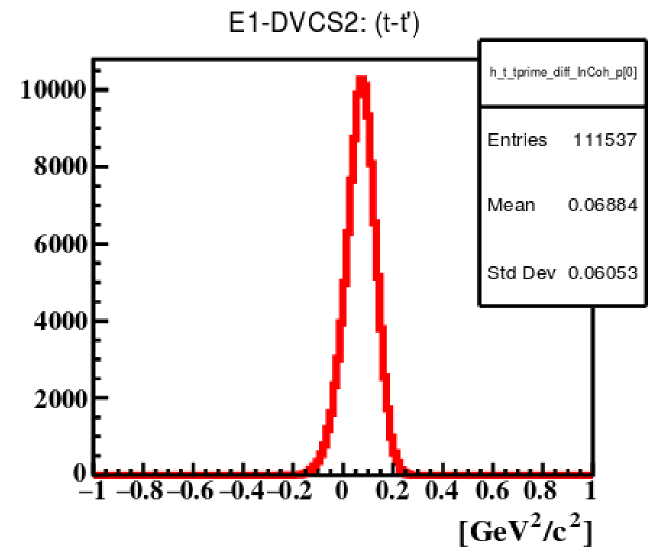
Fermi motion effect on the incoherent channel (1/2)

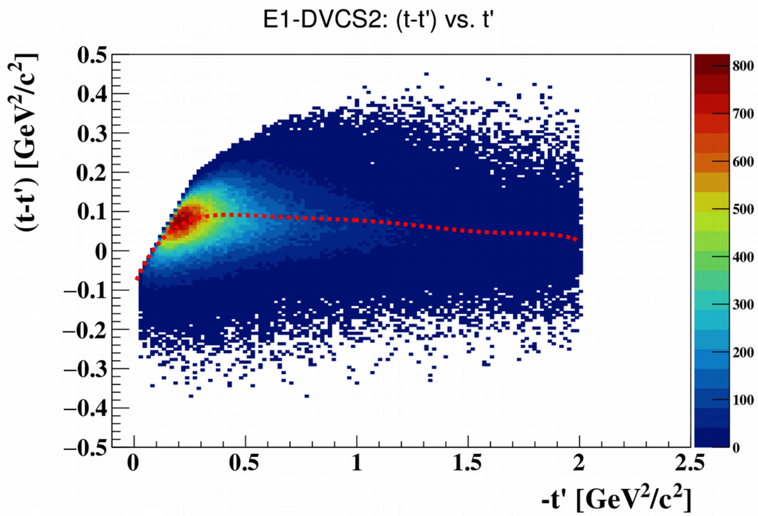
- typically t = t’
- t suffers from fermi motion
- t’ suffers from radiative effects

Evaluate the size radiative effects from free proton dvcs data (E1-DVCS1&2)

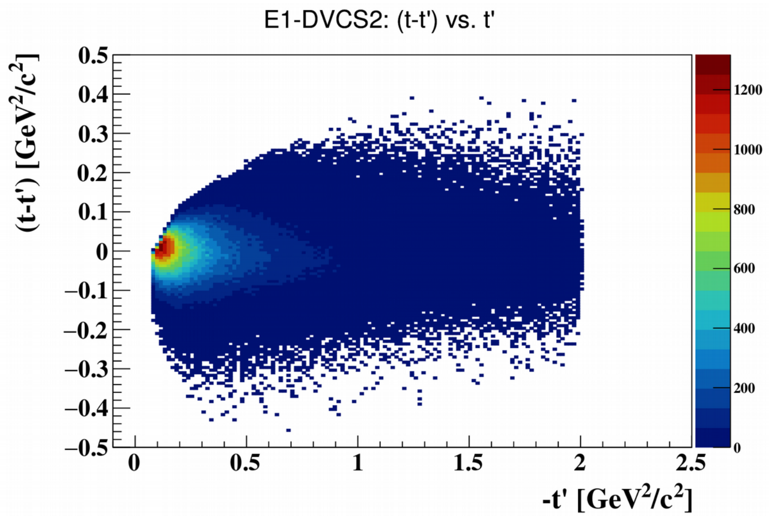








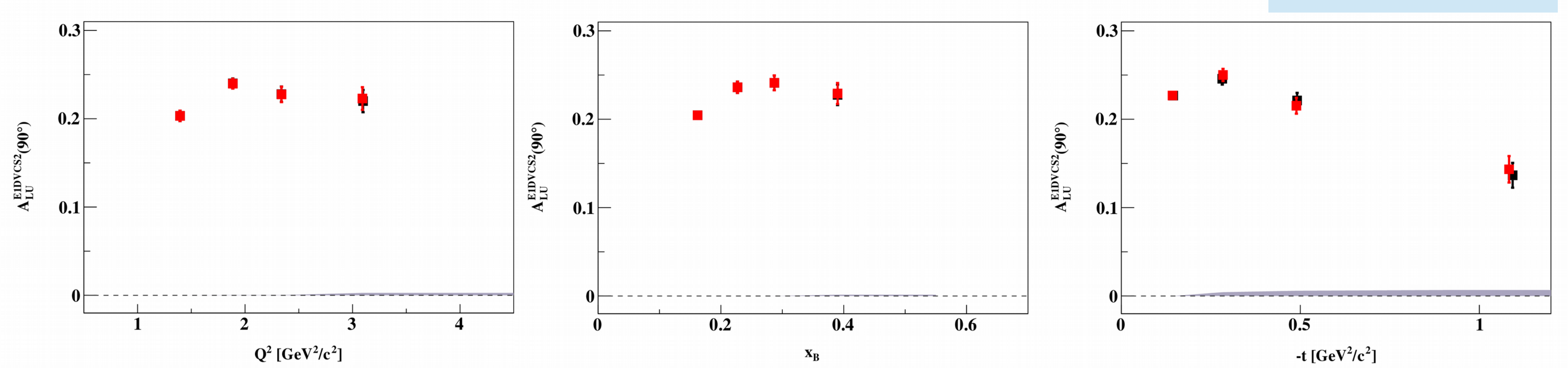
Corrections for radiative effects



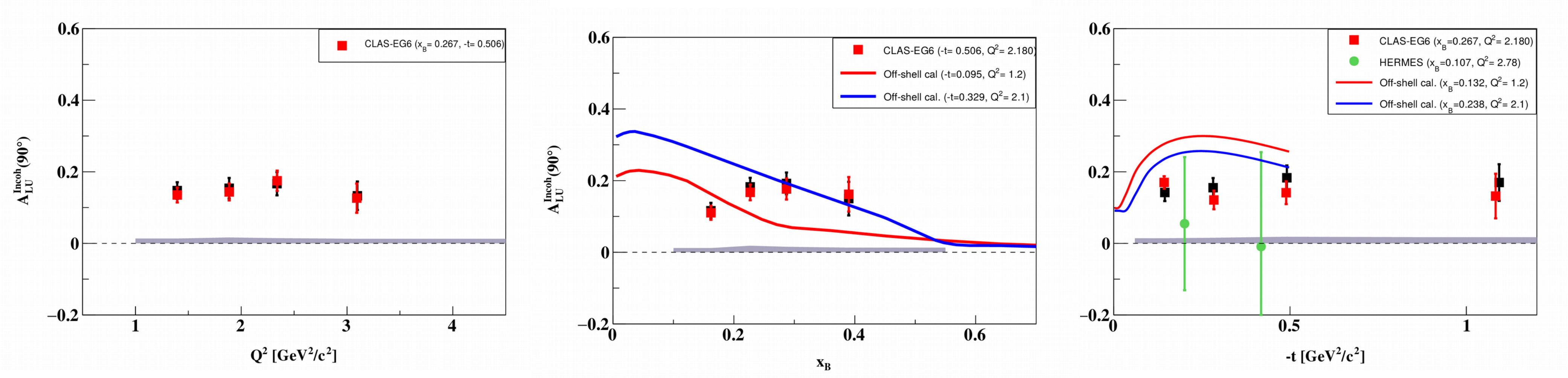
Fermi motion effect on the incoherent channel (2/2)

■ bins in t'
■ bins in t

- Induced systematic uncertainities based on free proton data

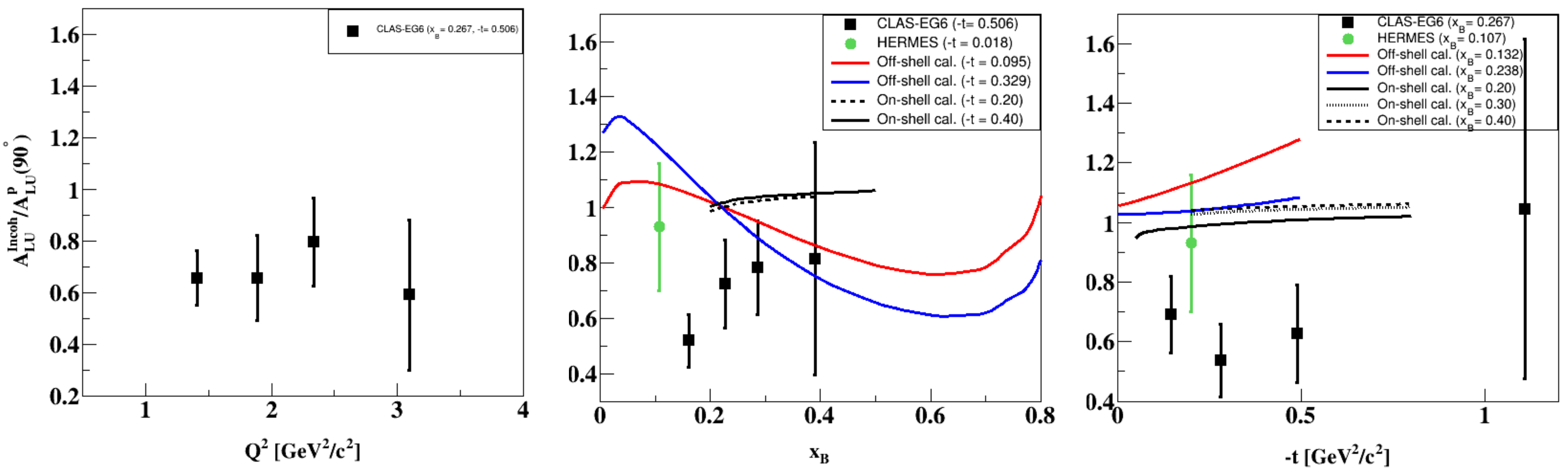


- EG6 incoherent DVCS A_{LU}@ φ = 90°



Generalized EMC ratio

◊ Comparing our measured incoherent asymmetries with the asymmetries measured in CLAS DVCS experiment on the proton.



◊ Scaling in Q^2 within the given error bars.

◊ The bound proton shows a lower asymmetry relative to the free one in the different bins in x_B.

◊ At small -t, the bound proton shows lower asymmetry than the free one.

◊ At high -t, the two asymmetries are compatible.

Future perspectives and proposals using "CLAS12 + ALERT" experimental setup

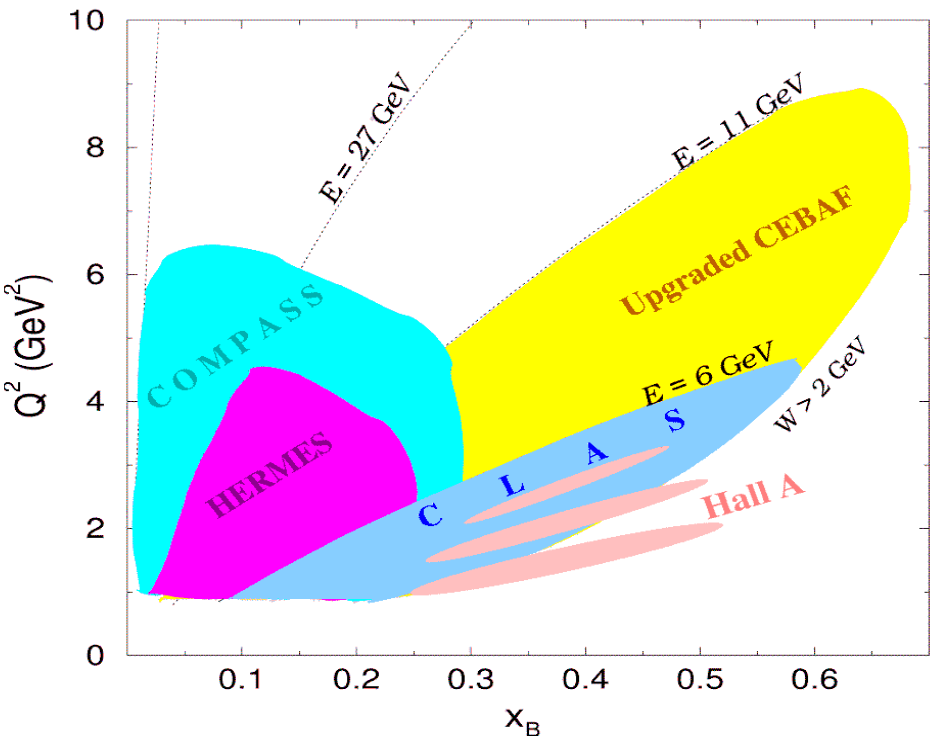
K. Hafidi, N. Baltzell, R. Dupre, M. Hattawy,
W. Armstrong, Z. E. Meziani, M. Paolone

◊ CLAS–E08-024 experiment:
→ 2D binning due to limited statistics and limited phase-space.

◊ We propose to measure:

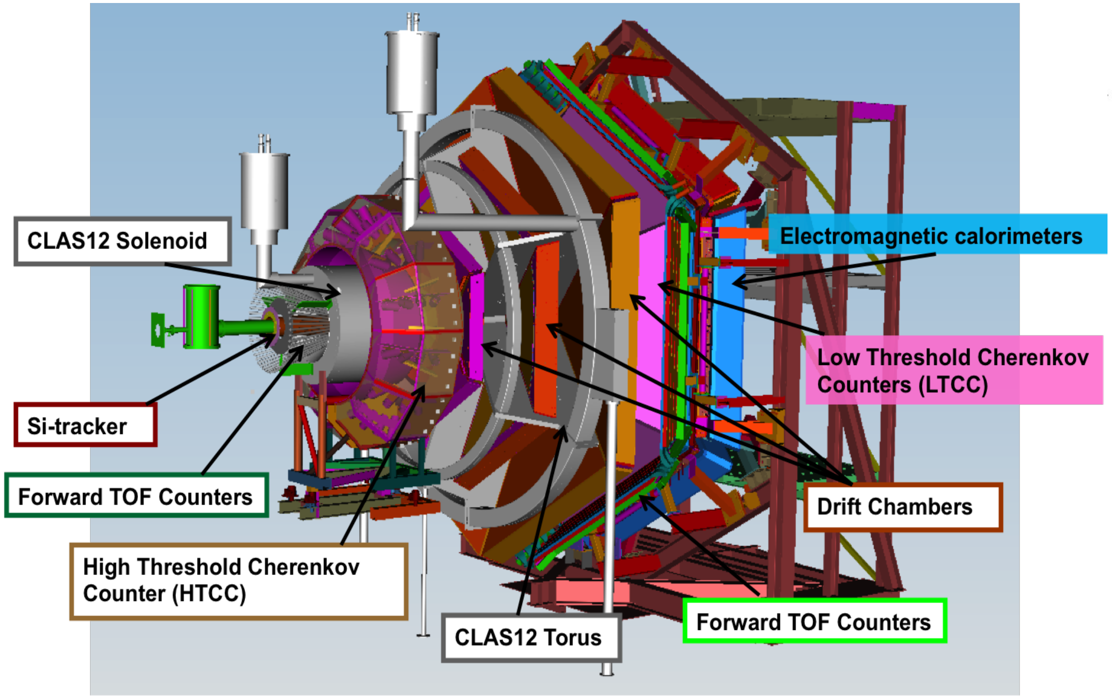
- Partonic Structure of Light Nuclei.
- Tagged DVCS Off Light Nuclei
- Tagged EMC on Light Nuclei

→ CLAS12-ALERT setup will allow higher statistics and wider kinematical coverage
→ 3D binning
→ More precise CFF extractions.

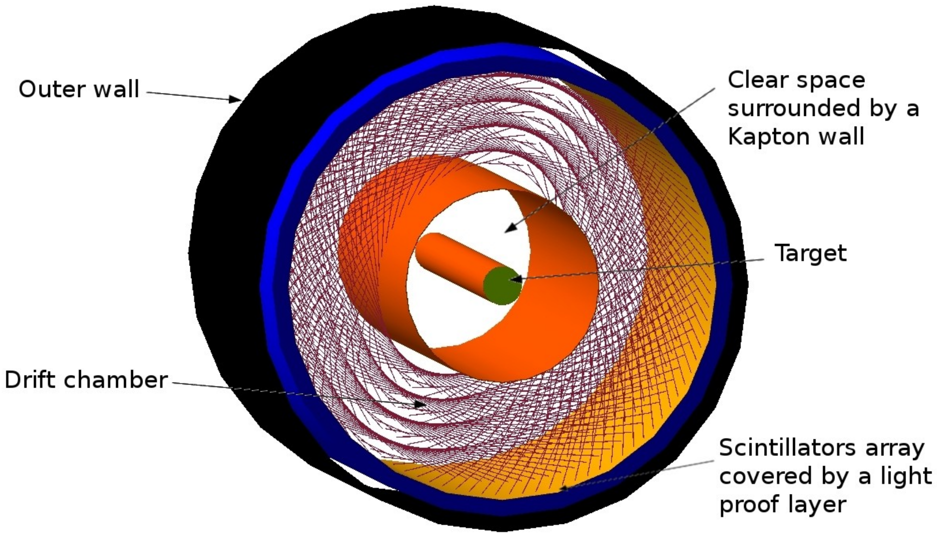


Proposed experimental setup:

CLAS12 detector



ALERT detector



- 300 mm long
- 90 mm diameter

- High luminosity & large acceptance.

- Measurement of deeply virtual exclusive, semi-inclusive, and inclusive processes

→ Can be included in the trigger.

→ Separate protons, deuterium, tritium, alpha, helium-3.

See W. Armestrong's talk for details

Summary and outlook

◊ CLAS – E08-024 experiment:

→ The first exclusive measurement of DVCS off ^{4}He.

→ The coherent DVCS shows a stronger asymmetry than the free proton as was expected from theory.

→ We performed the first ever experimental extraction of the real and imaginary parts of the He-4 CFF.

→ We extracted EMC ratios and compared them with theoretical predictions.

→ The bound proton has shown a different trend compared to the free one indicating the medium modifications of the GPDs.

◊ We are proposing a new generation nuclear physics experiment to extract quarks' and gluons' GPDs of He-4 using CLAS12 detector that will be upgraded with a low energy recoil tracker.

>> Wider kinematical coverage and better statistics that will allow 3D binnings for both the DVCS and DVMP channels

>> Will allow model independent extractions of the charge and the gluon densities of He-4.

Theoretical predictions of the EMC in 4He

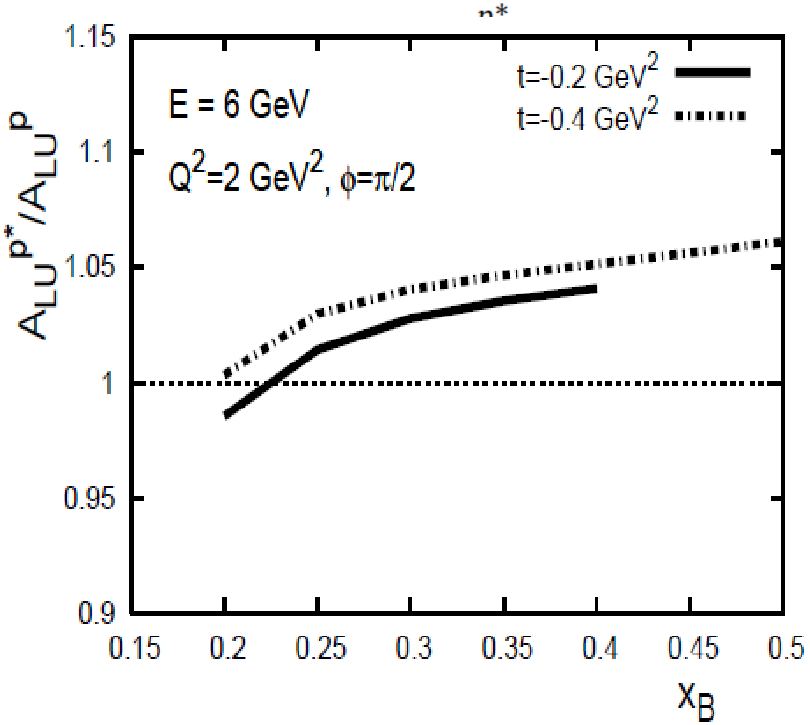
On-shell calculations:

(1) Impulse approximation

$GPD^{4He}(x,\xi,t) = \Sigma$ (free p and n GPDs)*$F_{4He}(t)$

(2) Medium modifications:

$$H^{q/p^*}(x,\xi,t,Q^2) = \frac{F_1^{p^*}(t)}{F_1^p(t)} H^q(x,\xi,t,Q^2),$$



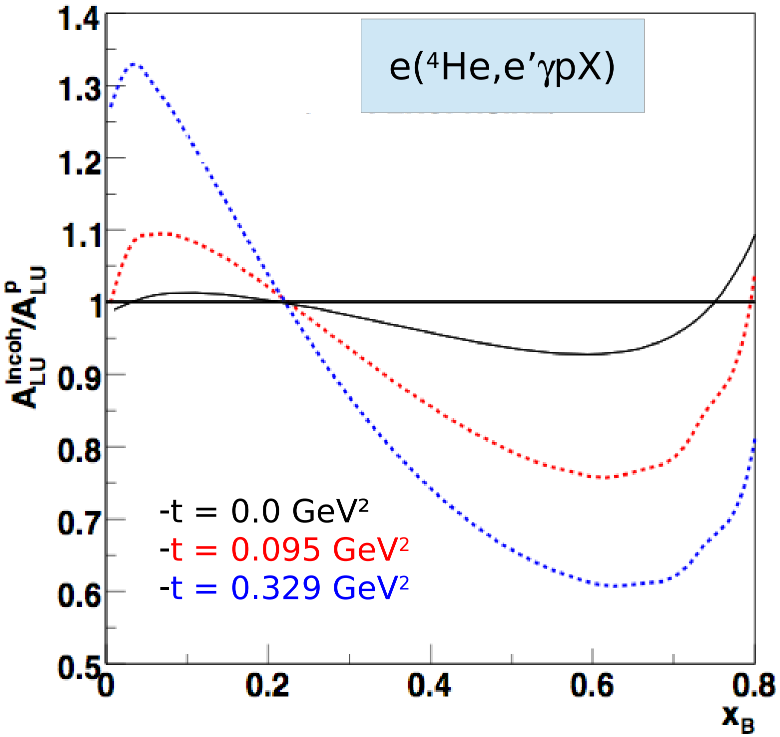
[V. Guzey, A. W. Thomas, K. Tsushima, PRC 79 (2009) 055205]

Off-shell calculations:

Nucleus = bound nucleons
+ nuclear binding effects

$$H^A(x,\xi,t) = \sum_N \int \frac{d^2P_\perp dY}{2(2\pi)^3} \frac{1}{A-Y} \boxed{\mathcal{A}_t \rho^A(P^2,P'^2)}$$
$$\times \sqrt{\frac{Y-\xi}{Y}} \left[H^N_{OFF}\left(\frac{x}{Y},\frac{\xi}{Y},P^2,t\right) - \frac{1}{4}\frac{(\xi/Y)^2}{1-\xi/Y} E^N_{OFF}\left(\frac{x}{Y},\frac{\xi}{Y},P^2,t\right) \right]$$

Nuclear spectral function



[S. Liuti, K.Taneja, PRC 72 (2005) 034902]

Nuclear DVCS measurements: HERMES

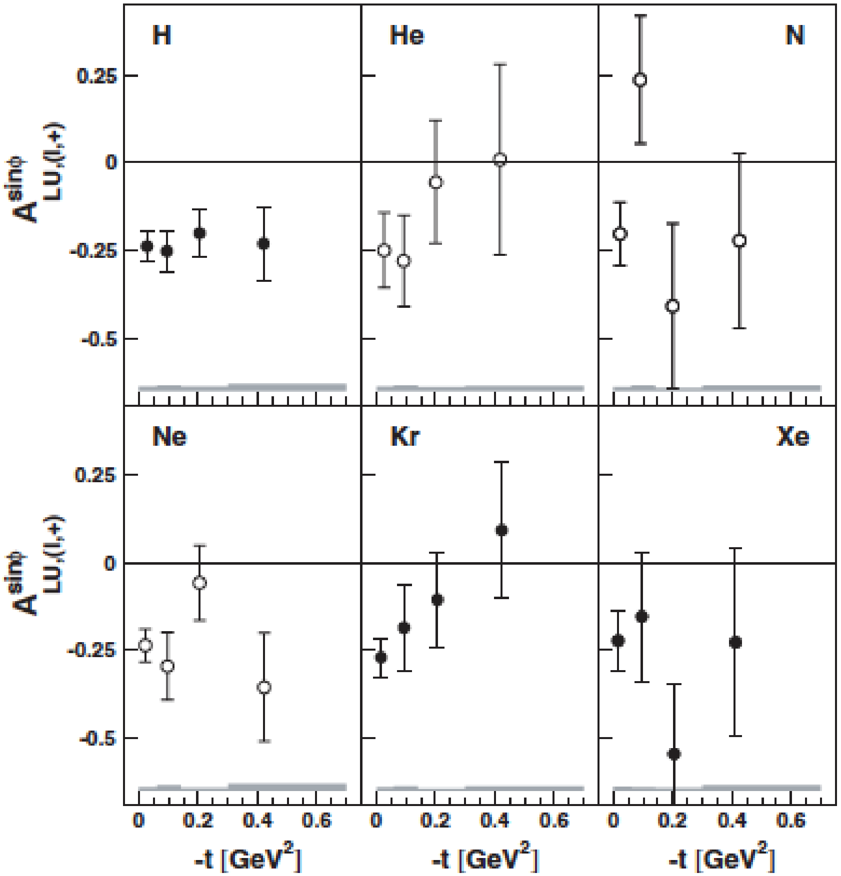
- The exclusivity is ensured via cut on the missing mass of eγX final state configuration.

- Coherent and incoherent separation depending on -t, i.e. coherent rich at small -t.

- Conclusions from HERMES:
  No nuclear-mass dependence has been observed.

In CLAS - E08-024, we measured EXCLUSIVELY the coherent and incoherent DVCS channels off ^{4}He

$$A_{LU}^{sin} = \frac{1}{\pi}\int_0^{2\pi} d\phi \, \sin\phi \, A_{LU}(\phi)$$

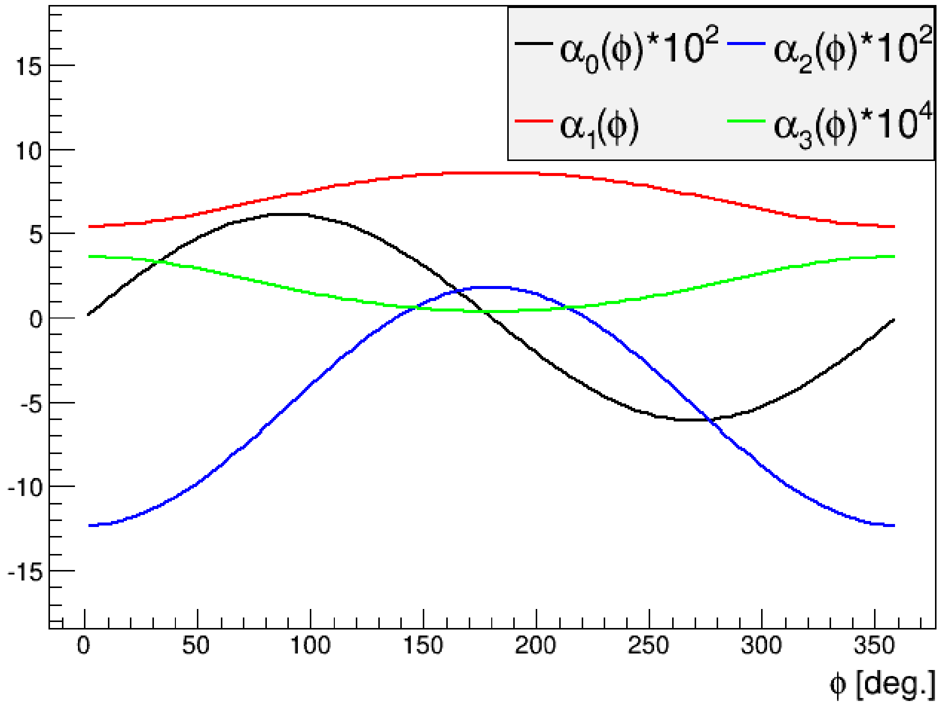


[A. Airapetian, et al., Phys Rev. C 81 (2010) 035202]

He-4 CFF extraction

$$A_{LU}(\phi) = \frac{\alpha_0(\phi)\,\Im m(\mathcal{H}_A)}{\alpha_1(\phi) + \alpha_2(\phi)\,\Re e(\mathcal{H}_A) + \alpha_3(\phi)\left(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\right)}$$

$$\begin{aligned}
\alpha_0(\phi) &= \frac{x_A(1+\varepsilon^2)^2}{y} S_{++}(1)\sin(\phi) \\
\alpha_1(\phi) &= c_0^{BH} + c_1^{BH}\cos(\phi) + c_2^{BH}\cos(2\phi) \\
\alpha_2(\phi) &= \frac{x_A(1+\varepsilon^2)^2}{y}\left(C_{++}(0) + C_{++}(1)cos(\phi)\right) \\
\alpha_3(\phi) &= \frac{x_A^2 t(1+\varepsilon^2)^2}{y}\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)\cdot 2\frac{2-2y+y^2+\frac{\varepsilon^2}{2}y^2}{1+\varepsilon^2}
\end{aligned}$$

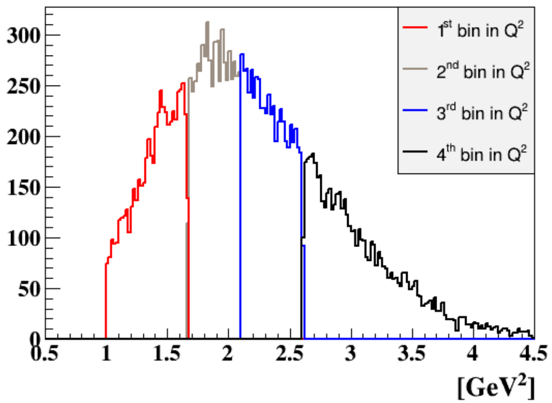


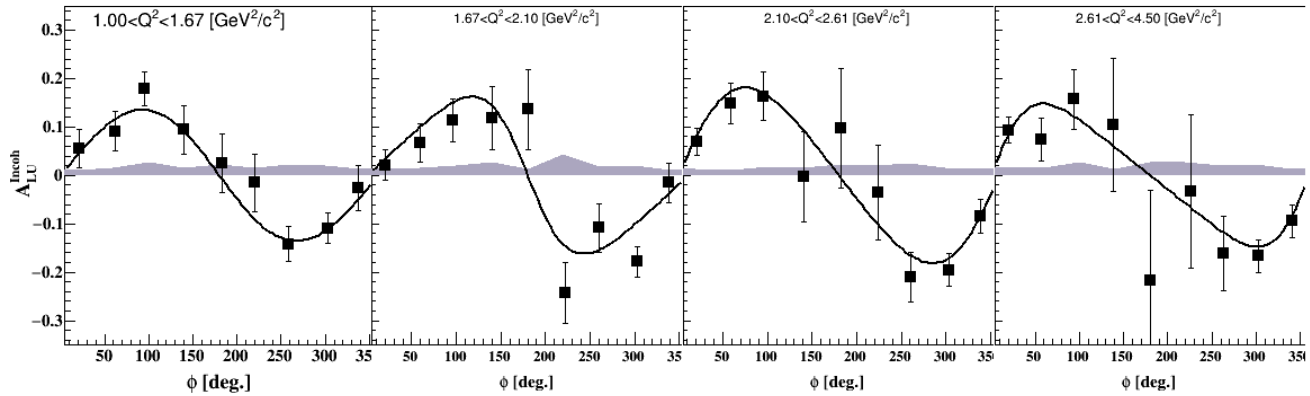
Incoherent beam-spin asymmetries

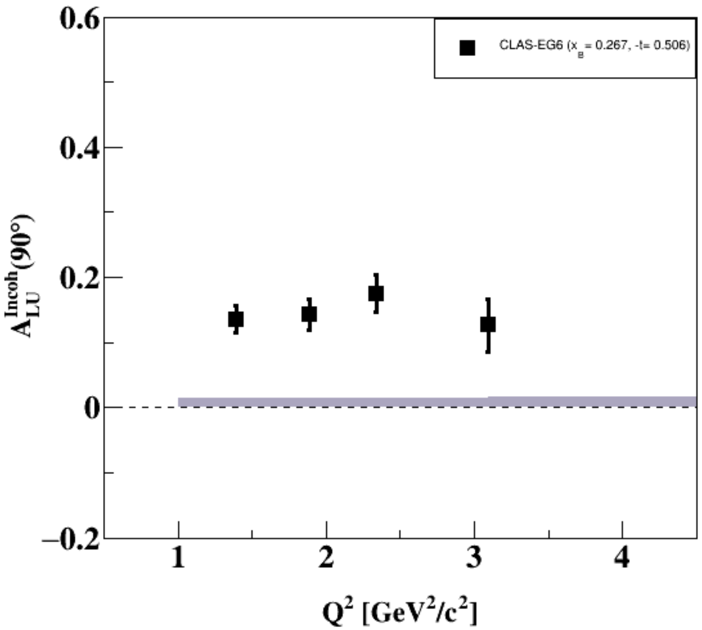
- 2D bins -t or x_B or Q^2 versus φ.

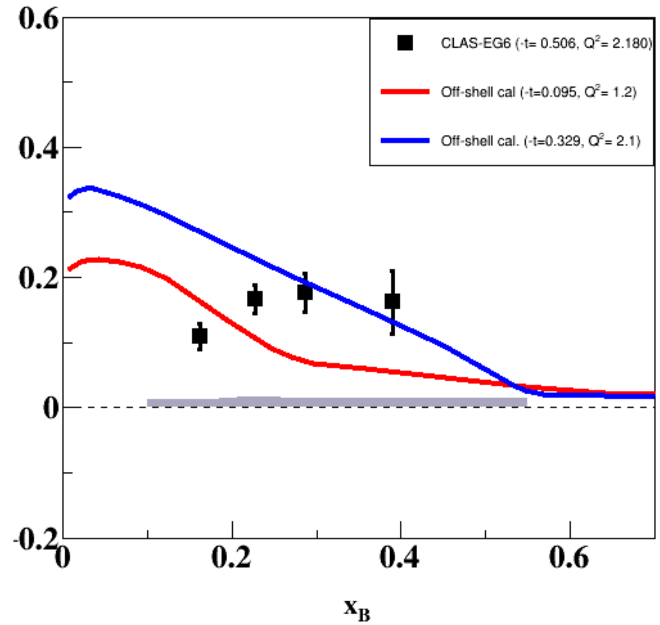
- Fit ALU signals: $\alpha * \sin(\phi)/(1+\beta * \cos(\phi))$

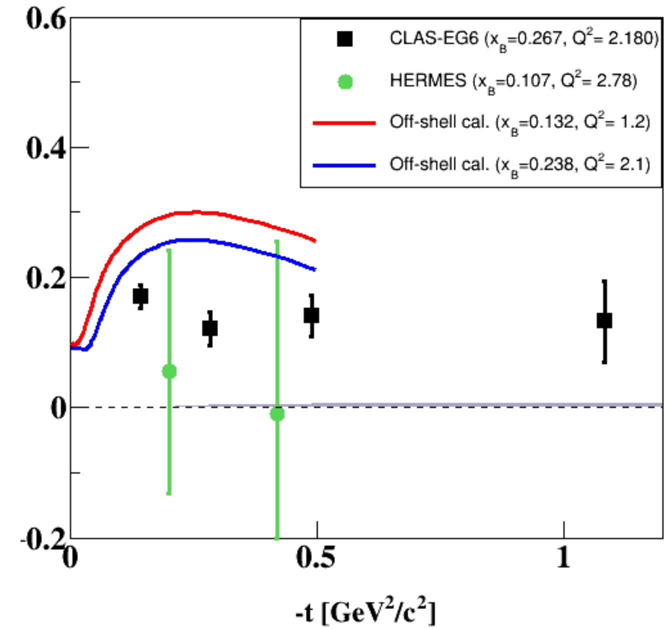
Q^2 of epγ events











[1] Off-shell: S. Liuti and S. K. Taneja.Phys. Rev., C72:032201, 2005.
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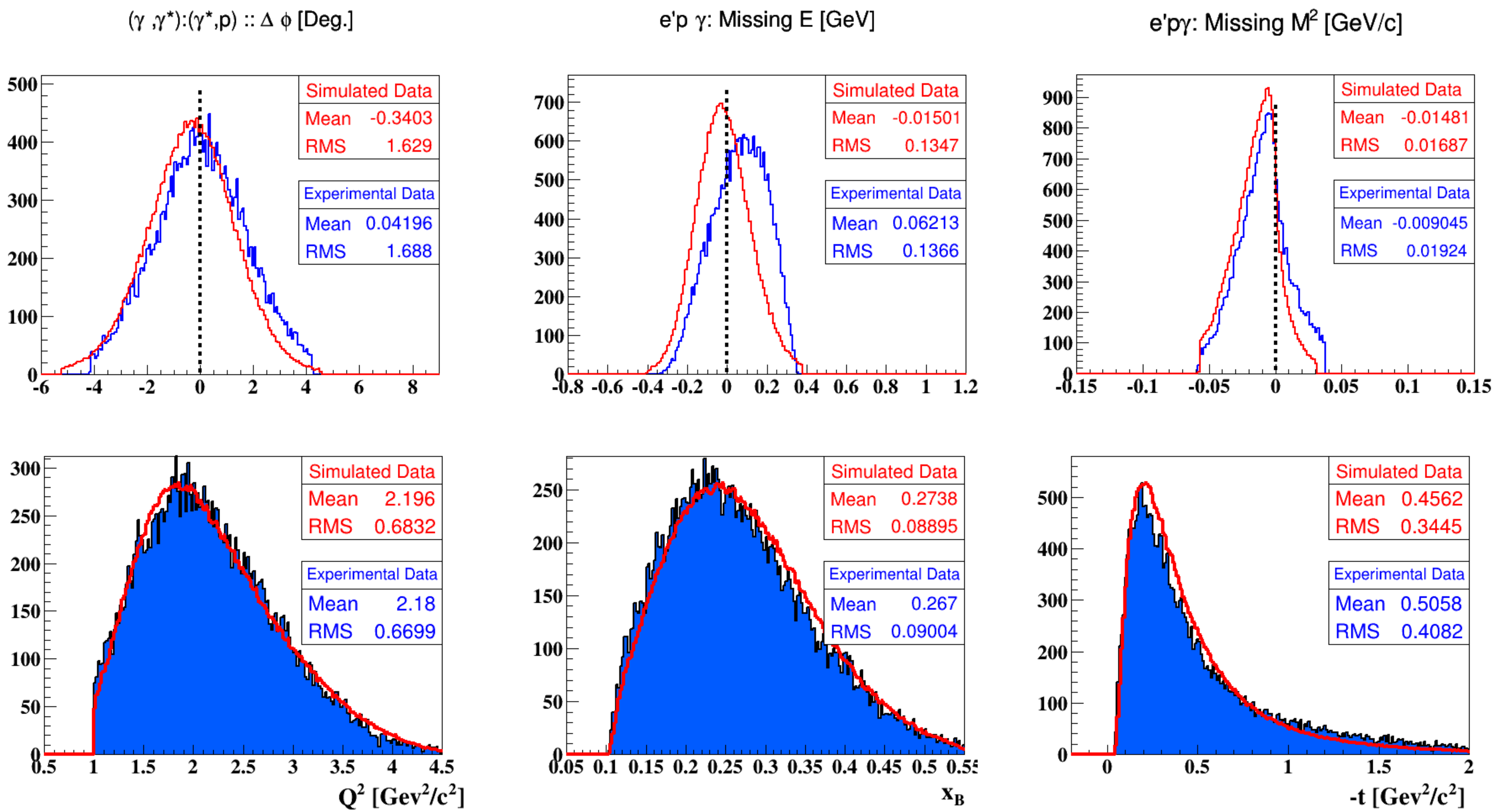
Incoherent DVCS events selection

◊ Only one e^-, at least 1γ and only one good p.

◊ Eγ > 2 GeV, W > 2 GeV/c^2 and Q^2 > 1 GeV^2.

◊ Exclusivity cuts (3 sigmas).



Monte Carlo simulation

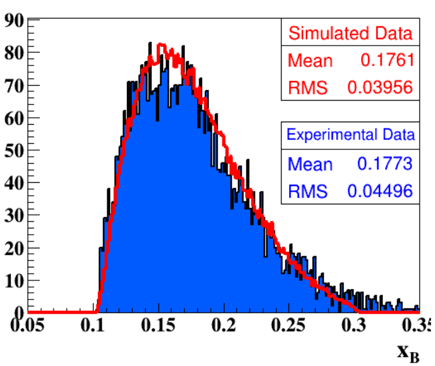
◊ **We use Monte Carlo for two goals:**

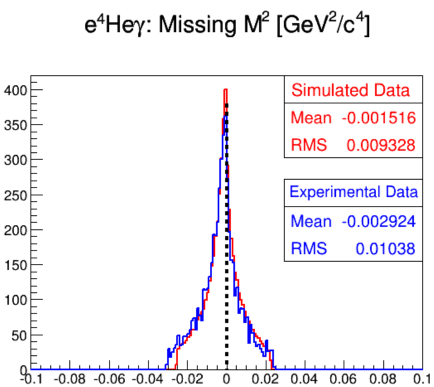
- Understanding the behavior of each particle type in our detectors
- Calculate the acceptance ratio for the purpose of the π^0 background subtraction

◊ **Simulation stages:**

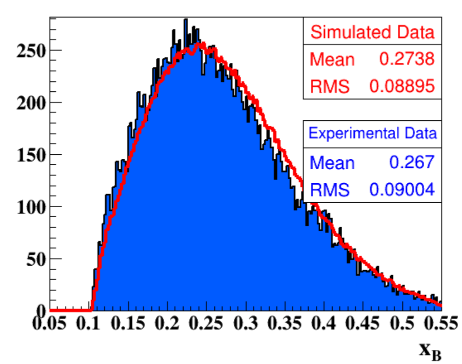
- **Event generator:** e ^{4}Heγ, e ^{4}Heπ^0, epγ and epπ^0 events are generated in their measured phase space (Q^2, x_B, $-t$, φ_h) following this parametrization of the cross section.
- **Simulation (GSIM):** GEANT3, describes the detectors' response to the different particles.
- **Smearing (GPP):** Makes the simulation more realistic by smearing the positions, energies and times.
- **Reconstruction (RECSIS):** (ADCs, TDCs) → physical quantities.

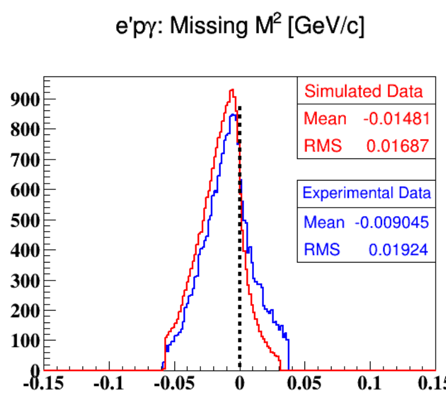
Coherent DVCS





Incoherent DVCS





Adequate agreement between data and simulation

Background Subtraction

◊ With our kinematics, the main background comes from the exclusive π⁰ channel,

$$e^4He \rightarrow e^4He\pi^0 \rightarrow e^4He\gamma\gamma \qquad\qquad ep \rightarrow ep\pi^0 \rightarrow ep\gamma\gamma$$

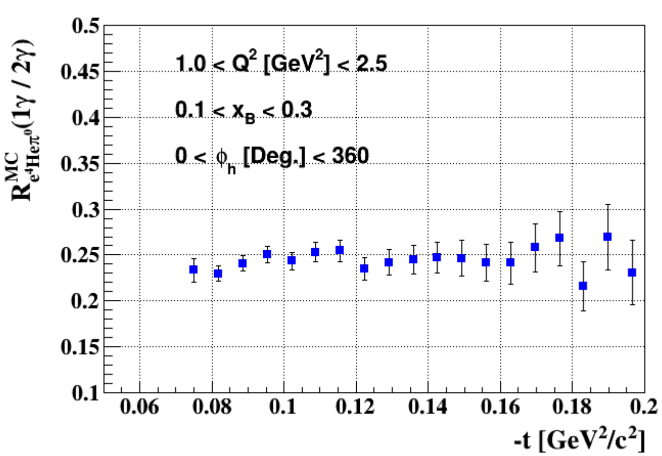
in which one photon from π⁰ decay is detected and passes the DVCS selection.

◊ We combine real data with simulation to compute the contamination of π⁰ to DVCS.

$$\overleftrightarrow{N}_{DVCS/BH} = \overleftrightarrow{N}^{Exp.}_{eHe\gamma} - \overleftrightarrow{N}^{Exp.}_{eHe\pi^0(1\gamma)} = \overleftrightarrow{N}^{Exp.}_{eHe\gamma} - \boxed{\left(\frac{N^{MC}_{eHe\pi^0(1\gamma)}}{N^{MC}_{eHe\pi^0(2\gamma)}}\right)} * \overleftrightarrow{N}^{Exp.}_{eHe\pi^0(2\gamma)}$$

Acceptance ratio (R (1γ/2γ))

→ In -t bins (integrated over φ_h, Q^2, x_B):



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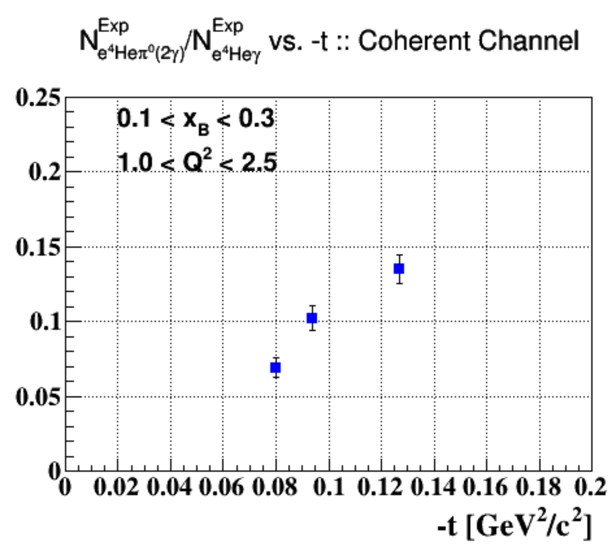

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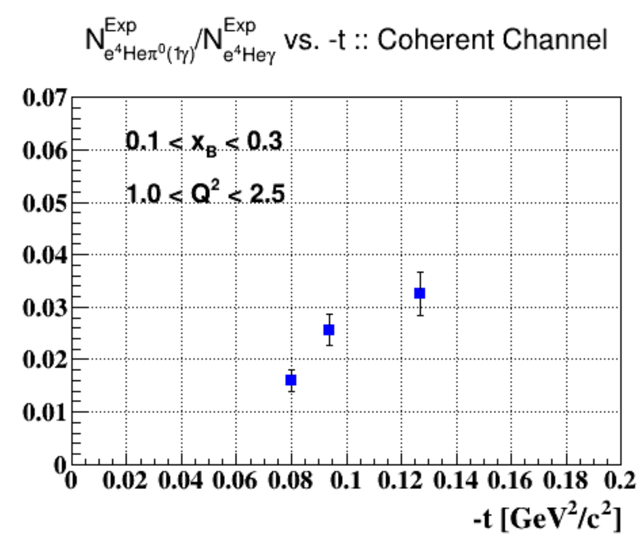
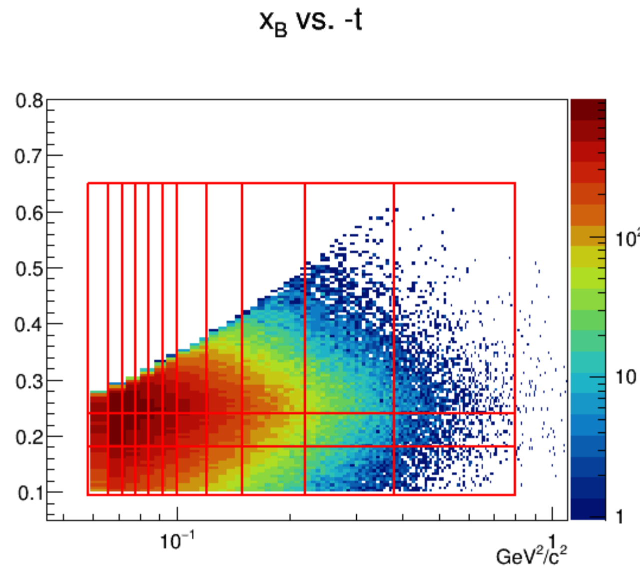


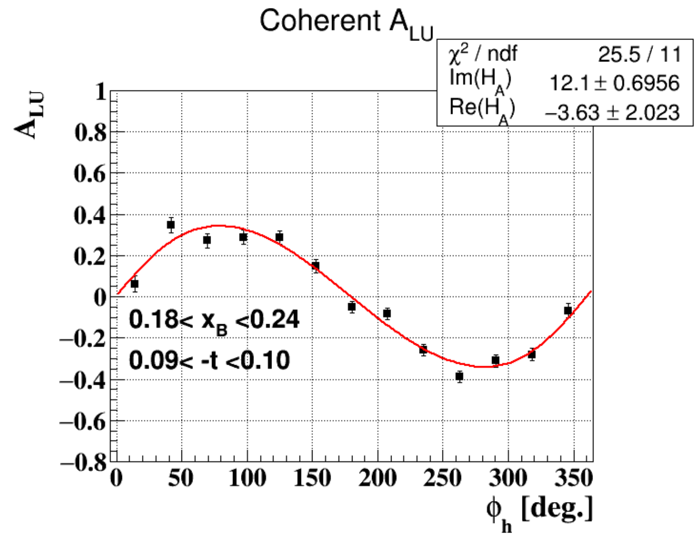
◊ Background yield ($N^{Exp}_{e^4He\pi(1\gamma)}$ / $N^{Exp}_{e^4He\gamma}$) ratio ~ 2-4% (8-11%) in $e^4He\gamma$ ($ep\gamma$) channel.

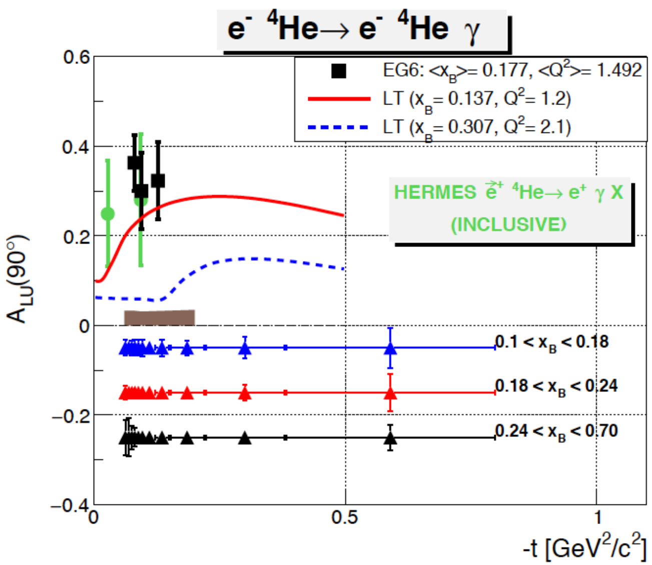
DVCS off He-4: Projected precisions

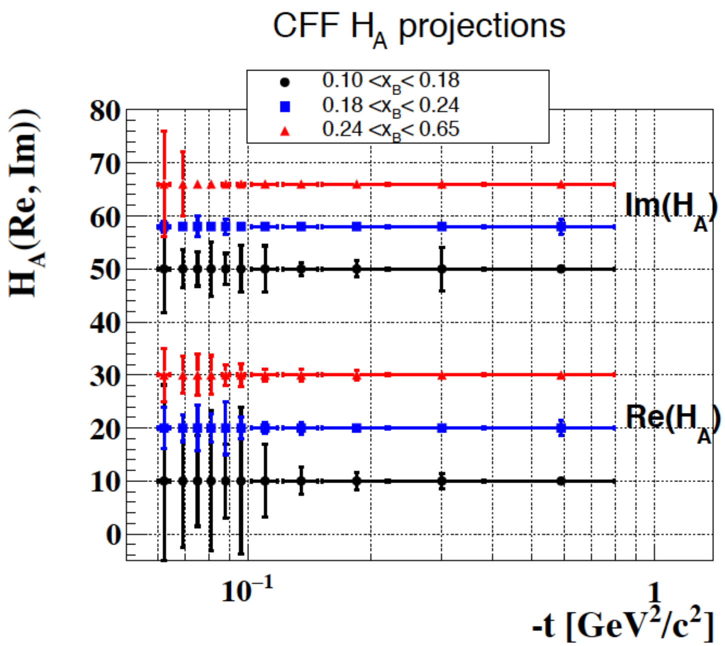
The statistical error bars are calculated for:

- 20 days at a luminosity of 3.0×10^{34} cm^{-2}s^{-1}.
- 10 days at a luminosity of 6×10^{34} cm^{-2}s^{-1}.



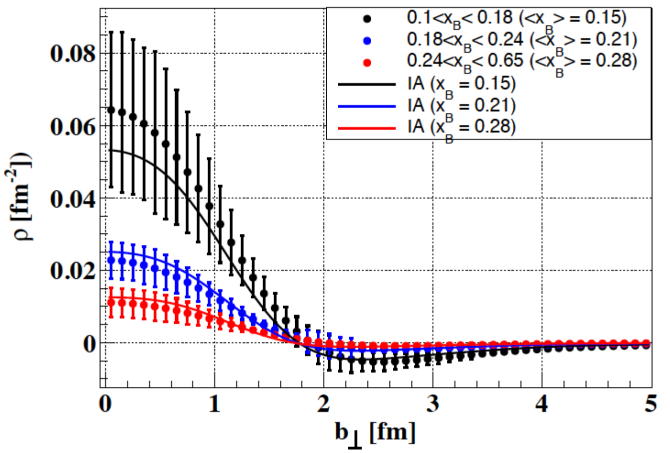






$$\rho(x,0,b_\perp) = \int_0^\infty J_0(b\sqrt{t}) H^A(x,0,t) \frac{\sqrt{t}}{2\pi} d\sqrt{t}$$

Projected charge profile precisions



φ production off He-4: Gluon profiles

$$e + {}^4He \rightarrow e' + {}^4He + \phi(K^+ + K^-) \qquad \frac{d\sigma_L}{dt} = \frac{1}{(\varepsilon + 1/R)\Gamma(Q^2, x_B, E)} \frac{d^3\sigma}{dQ^2 dx_B dt}$$

R can be extracted from the angular distribution of the kaon decay
In the phi helicity frame, assuming s-channel helicity conservation:

$$W(\cos\theta_H) = \frac{3}{4}\left[(1 - r^{04}_{00}) + (3r^{04}_{00} - 1)\cos^2\theta_H\right]$$

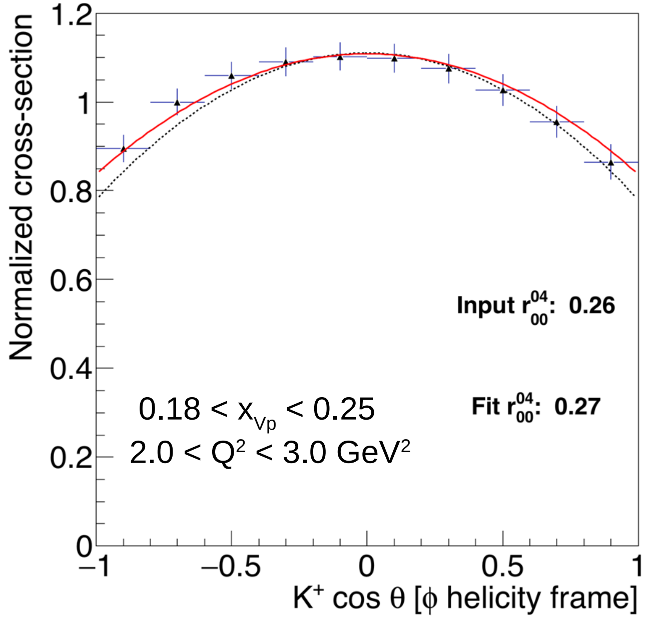
Angular distribution amplitude

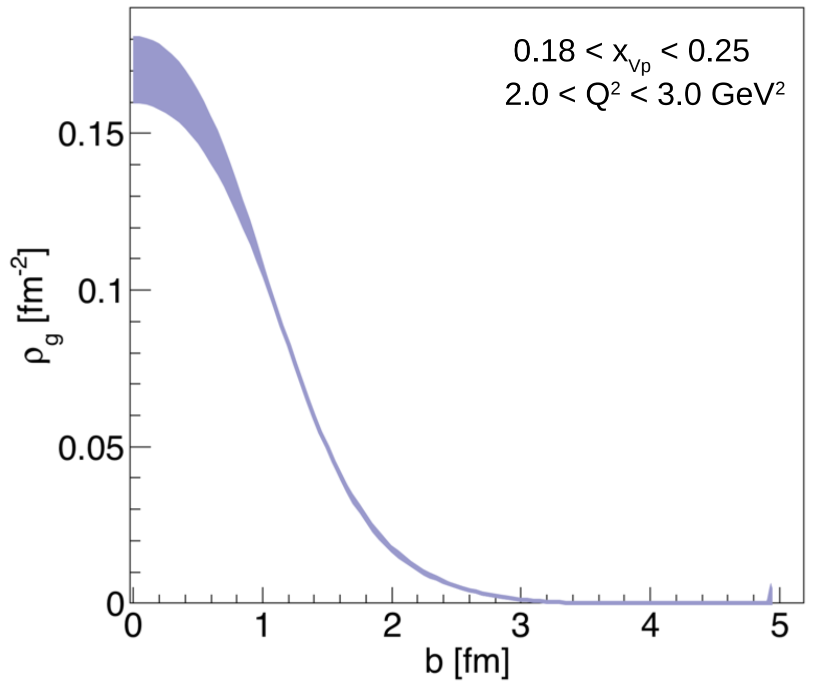
Spin-density matrix coefficient: $r^{04}_{00} = \frac{\epsilon R}{1 + \epsilon R}$

Angle of kaon decay In phi helicity frame

Gluon density calculation:

$$\rho_g(x, 0, b_\perp) \rightarrow \int_0^\infty J_0(b\sqrt{t}) \sqrt{\frac{d\sigma_L}{dt}} \frac{\sqrt{t}}{2\pi} d\sqrt{t}$$

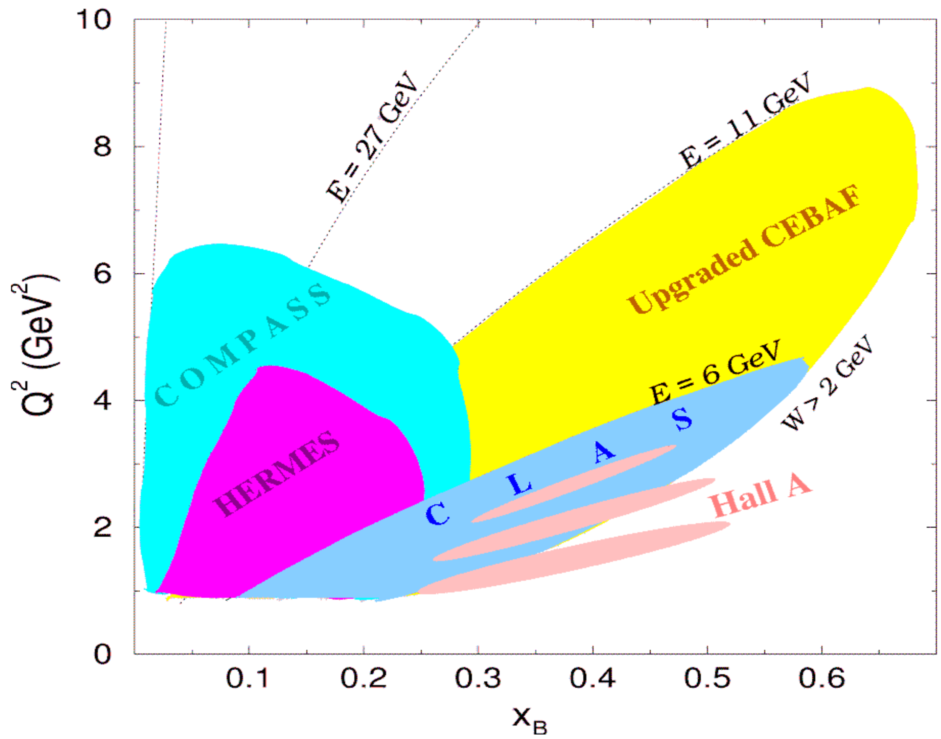




Design parameters of CLAS12

	Forward detector	Central detector
Angular range		
Tracks	$5 - 40^\circ$	$35 - 125^\circ$
Photons	$2.5 - 40^\circ$	n.a.
Resolution		
$\delta p/p$	$< 1\%$ @ 5 GeV/c	5% @ 1.5 GeV/c
$\delta\theta$	< 1 mr	< 10-20 mr
$\delta\phi$	< 3 mr	< 5 mr
Photon detection		
Energy	> 0.15 GeV	n.a.
$\delta\theta$	4 mr @ 1 GeV	n.a.
Neutron detection		
Efficiency	< 0.7	under dev.
Particle ID		
e/π	Full range	n.a.
π/p	Full range	< 1.25 GeV/c
π/K	Full range	< 0.65 GeV/c
K/p	< 4 GeV/c	< 1 GeV/c
$\pi \to \gamma\gamma$	Full range	n.a.
$\eta \to \gamma\gamma$	Full range	n.a.

DVCS worldwide effort



CERN
COMPASS
p-DVCS: X-sec,BSA,BCA, tTSA,lTSA,DSA

DESY	
HERMES	***H1/ZEUS***
p-DVCS BSA,BCA, TTSA, LTSA,DSA	p-DVCS X-sec,BCA

JLAB	
Hall A	***Hall B***
p,n,d -DVCS: X-sec	p-DVCS: BSA,LTSA, DSA, X-sec Helium-4: BSA

Promising future experiments with JLab upgrade and COMPASSII